Design of Tunable Metamaterial Operating near 90 GHz

Karol Tarnowski[*1], and Wlodzimierz Salejda[1]
[1]Institute of Physics, Wroclaw University of Technology, Wroclaw, Poland
*Corresponding author: postal address: Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland; email address: karol.tarnowski@pwr.wroc.pl

Abstract: In our paper we present numerical investigation of tunability of metamaterial cell containing nematic liquid crystal. We have performed calculation of scattering parameters (S_{11}, S_{21}) with finite element method. Next we have retrieved effective refractive index, permittivity and permeability. Performing simulations for different assumed orientation of liquid crystals molecules we have evaluated tunability.

Keywords: metamaterial, nematic liquid crystal, tunability.

1. Introduction

Currently there is much interest in electromagnetic metamaterials [1-7]. In our work we have focused on numerical investigation of tunability of designed metamaterial. Typically negative value of real part of refractive index is achieved in structures which combine metallic split-ring resonators and thin-wires. Moreover investigated design contains nematic liquid crystal layer to obtain tunability. One can control propagation of electromagnetic waves by changing orientation of liquid crystal molecules. The considered cell can be fabricated within available technology.

2. Numerical model

2.1. Boundary condition

In performed simulations we have considered interaction of polarized light with metamaterial cell. We have limited our investigation to single metamaterial cell by applying appropriate boundary condition. They are presented in figure 1. The colors correspond to:

- red – PEC – perfect electric conductor,
- blue – PMC – perfect magnetic conductor,
- green – plane wave port.

On the opposite faces the same boundary condition is applied. The incident plane wave is propagating along y-direction with electric field component along x-direction and magnetic field component along z-direction.

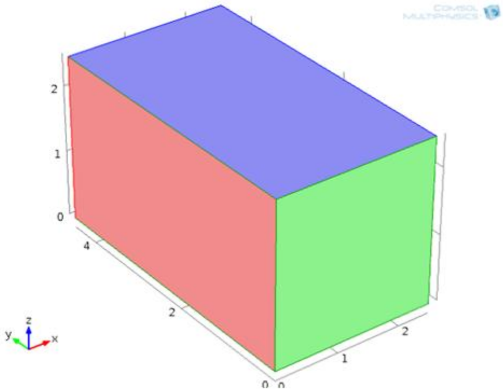


Figure 1. Boundary condition used in numerical model.

2.2. Materials

In presented calculations we have used four materials: air, gold, quartz and nematic liquid crystal. Each is highlighted in corresponding part of figure 2.

The values of permittivities, permeabilities, and conductivities are:

- for air: $\varepsilon = 1$, $\mu = 1$, $\sigma = 0$ S/m;
- for gold: $\varepsilon = 1$, $\mu = 0.99996$, $\sigma = 45.6e6$ S/m;
- for quartz: $\varepsilon = 4.5$, $\mu = 1$, $\sigma = 0$ S/m.

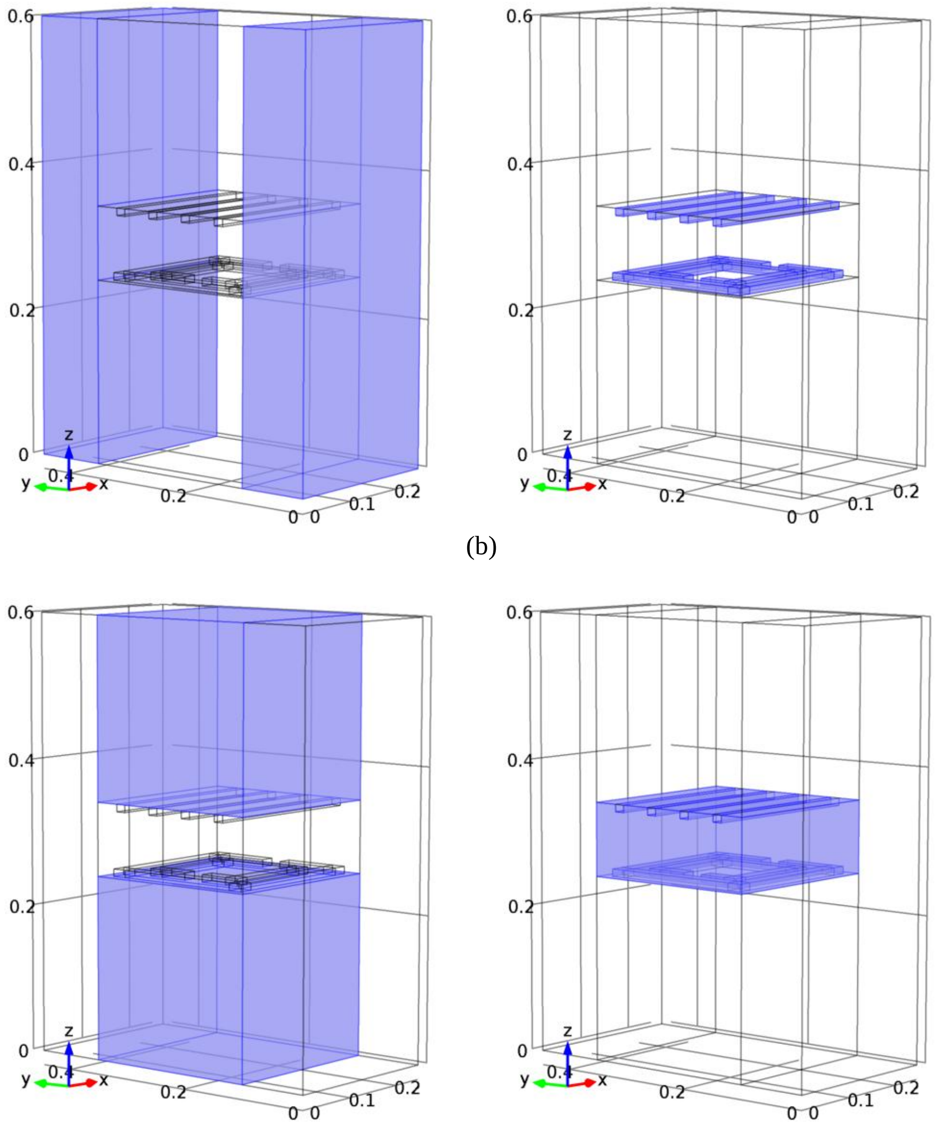
For nematic liquid crystal $\mu = 1$, $\sigma = 0$ S/m, and permittivity is given by:

- $\varepsilon_{\|} = 4.004336\cdot(1-4.44\cdot10^{-2}i)$;
- $\varepsilon_{\perp} = 2.566052\cdot(1-2.65\cdot10^{-2}i)$.

The values of permittivities for nematic liquid crystals were taken from measurements [8].

In order to evaluate tunability, simulations were performed for three different orientations of nematic liquid crystal molecules. Explicitly:

- along x-axis ($\varepsilon_x = \varepsilon_{\|}$, $\varepsilon_y = \varepsilon_{\perp}$, $\varepsilon_z = \varepsilon_{\perp}$),
- along y-axis ($\varepsilon_x = \varepsilon_{\perp}$, $\varepsilon_y = \varepsilon_{\|}$, $\varepsilon_z = \varepsilon_{\perp}$),
- along z-axis ($\varepsilon_x = \varepsilon_{\perp}$, $\varepsilon_y = \varepsilon_{\perp}$, $\varepsilon_z = \varepsilon_{\|}$).



(a) (b) (c) (d)

Figure 2. Different materials used in numerical model. (a) air, (b) gold, (c) quartz, (d) nematic liquid crystal. The axes units are millimeters.

2.3. Geometry

The considered cell has following dimensions. The quartz plates have thicknesses of 250 μm, the nematic liquid crystal layer is 100 μm thick and gold elements are 10 μm thick. The dimensions of gold elements in xy-plane are denoted in figure 3 and gathered in table 1.

Table 1. Dimensions of gold elements.

quantity	value [μm]
a	250
b	20
c	14
d	110
e	20
f	220
g	30

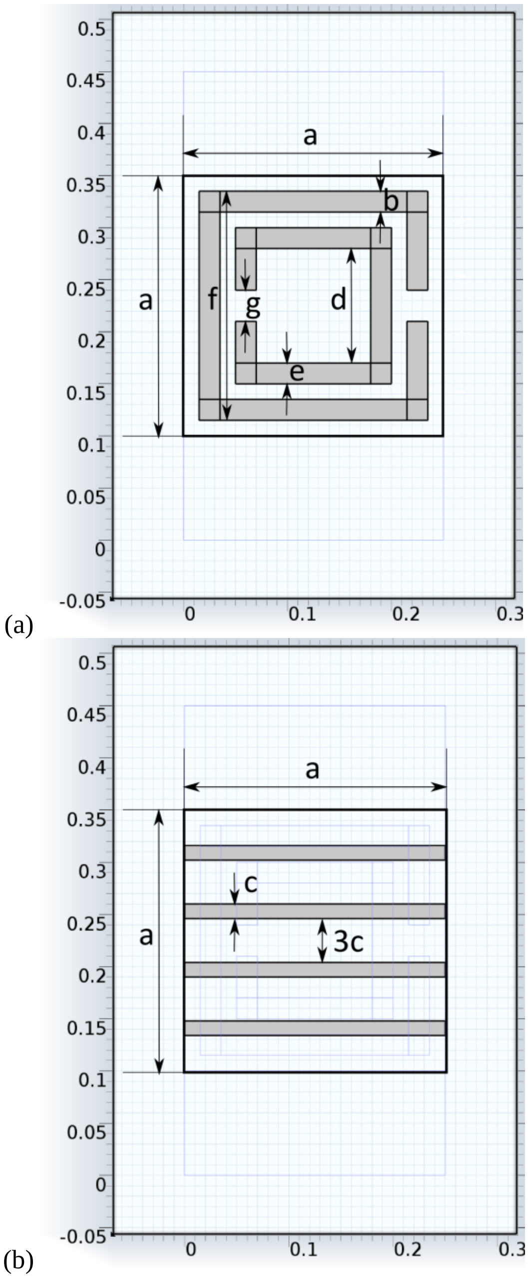


Figure 3. Dimensions of gold elements. (a) split-ring resonators (SRRs), (b) thin wires (TWs). The axes units are millimeters.

2.4. Frequency range

The investigated cell was designed to obtain negative value of real part of refractive index near 90 GHz. The simulations were performed in frequency range from 70 to 100 GHz.

3. Results

Three possible orientation of nematic liquid crystal were considered. The highest change of properties was observed in numerical experiment between orientation along x-direction and along z-direction.

In figures 4 and 5 the scattering parameters (S_{11}, S_{21}) caluculated with Comsol Multiphysics RF Module for two orientations are presented in Cartesian (real, imaginary) and polar (absolute value, argument) coordinate systems. Those data

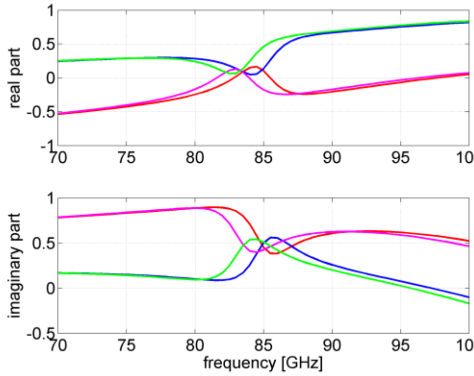


Figure 4. Scattering parameters calculated with finite element method expressed in Cartesian coordinate system (real and imaginary parts). Colors correspond to: red – S11 NLC molecules oriented along z axis; blue – S21 NLC molecules oriented along z axis; magenta – S11 NLC molecules oriented along x axis; green – S21 NLC molecules oriented along x axis.

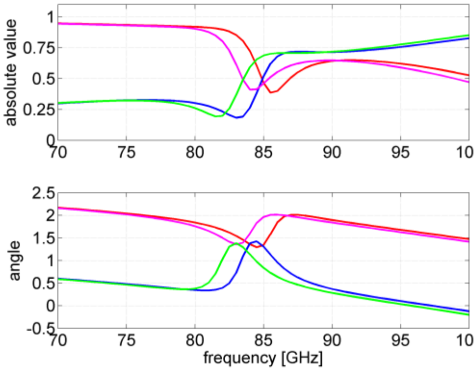


Figure 5. Scattering parameters calculated with finite element method expressed in polar coordinate system (absolute value and angle). Colors correspond to: red – S11 NLC molecules oriented along z axis; blue – S21 NLC molecules oriented along z axis; magenta – S11 NLC molecules oriented along x axis; green – S21 NLC molecules oriented along x axis.

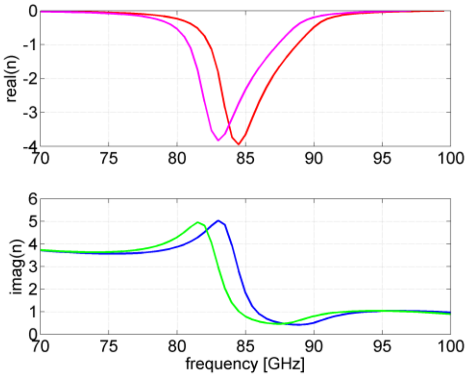


Figure 6. Effective refractive indices retrieved from scattering parameters. Colors correspond to: red and blue – NLC molecules oriented along z axis; magenta and green – NLC molecules oriented along x axis.

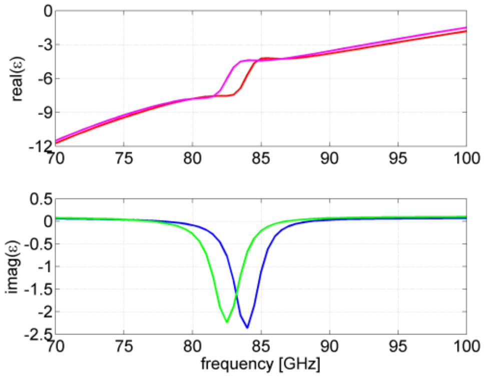


Figure 7. Effective permittivites retrieved from scattering parameters. Colors correspond to: red and blue – NLC molecules oriented along z axis; magenta and green – NLC molecules oriented along x axis.

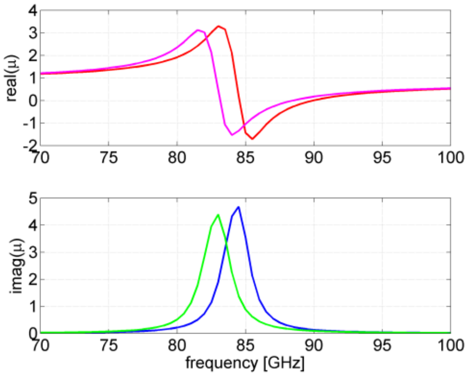


Figure 8. Effective permeabilities retrieved from scattering parameters. Colors correspond to: red and blue – NLC molecules oriented along z axis; magenta and green – NLC molecules oriented along x axis.

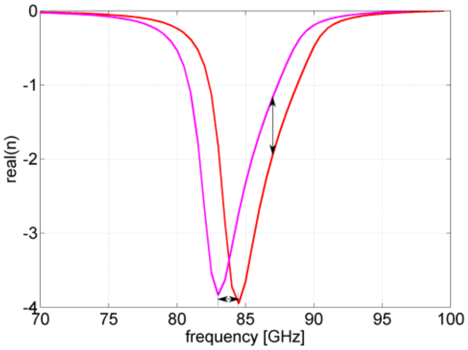


Figure 9. Tuning denoted as shift of minimum of real part of effective refractive index and as change of value at fixed frequency. Colors correspond to: red – NLC molecules oriented along z axis; magenta – NLC molecules oriented along x axis.

were input for algorithm of retrieving effective medium parameters. The robust method for performing this retrieval calculation was presented by Chen et al. [9].

The figures 6, 7 and 8 present the calculated effective refractive index, effective permittivity and effective permeability. In figure 9 the change of real part of refractive index is shown. Tunability can be calculated as shift of minimum real part of effective refractive index and as change of its value. In the first case the relative shift is about 1.8% and in the second the relative change is 67%.

4. Conclusions

We have performed numerical investigation of tunable metamaterial cell which is achieved by reorientation of nematic liquid crystal layer. We have validated structure before fabrication. We believe that our work could be used to further optimization of electromagnetic devices (phase-shifters, filters etc.).

5. References

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6. Acknowledgements

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